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ABSTRACT

We have developed a conceptual design for a 50 TW / 20 J short-pulse laser for performing high-energy-density plasma physics experiments at the Nevada Terawatt Facility of the University of Nevada, Reno. The purpose of the laser is to develop proton and x-ray radiography techniques, to use these techniques to study z-pinch plasmas, and to study deposition of intense laser energy into both magnetized and unmagnetized plasmas.

Our design uses a commercial diode-pumped Nd:glass oscillator to generate 3-nJ, 200-fs mode-locked pulses at 1059 nm. An all-reflective grating stretcher increases pulse duration to 1.1 ns. A two-stage chirped-pulse optical parametric amplifier (OPCPA) using BBO crystals boosts pulse energy to 12 mJ. A chain using mixed silicate-phosphate Nd:glass increases pulse energy to 85 J while narrowing bandwidth to 7.4 nm (FWHM). About 50 J is split off to the laser target chamber to generate plasma while the remaining energy is directed to a roof-mirror pulse compressor, where two 21 cm x 42 cm gold gratings recompress pulses to ~350 fs. A 30-cm-focal-length off-axis parabolic reflector (OAP) focuses ~20 J onto target, producing an irradiance of 10^{19} W/cm^2 in a 10-μm-diameter spot.

This paper describes planned plasma experiments, system performance requirements, the laser design, and the target area design.

I. INTRODUCTION

Currently, high-energy-density plasma-physics experiments at the University of Nevada's Nevada Terawatt Facility (NTF) near Reno center on the Zebra, a 2 MA, 2 TW z-pinch plasma generator. Over the past several decades, ultra-intense short-pulse laser technology and its application have matured, with sub-picosecond laser pulses used to produce highly localized sources of x-rays, proton beams, and even neutrons. Such localized sources are ideal for radiographic studies of rapidly evolving phenomena in plasma and for characterizing distributions of particle densities and fields. Accordingly, the University of Nevada (UNR) has undertaken the construction and activation of a short pulse 50 TW / 20 J laser, which, when combined with the Zebra, will enable unique characterizations of z-pinch plasmas through the use of both x-ray and proton-beam radiography. UNR has partnered with Lawrence Livermore National Laboratory for the design and construction of the laser, and with Los Alamos National Laboratory for the design and construction of the target area. Laser system activation is scheduled in 2004.

II. PLANNED EXPERIMENTS

The 50 TW / 20 J laser we have designed is capable of generating x-rays over a broad range of energies for characterizing various z-pinch features using radiography. However, X-rays that are either too soft or too hard are mostly stopped or mostly transmitted by the target, respectively, yielding images with poor contrast. Thus, to improve the quality of radiographic images of z-pinch plasma, we have planned experiments to determine optimum x-ray energies as well as optimum laser and target conditions for generating them. These planned studies encompass hard K-shell radiation, since the requisite irradiance of ~ 10^{19} W/cm^2 is within the performance limits of our laser design.

The 50 TW / 20 J laser is also well suited for generating proton beams. High-resolution radiography has been demonstrated with the 270-fs, 30-J laser at LULI (in France), with the 500-fs, 0.5-J (at 527 nm) Trident laser at Los Alamos National Laboratory, and with the Vulcan laser at the Rutherford-Appleton Laboratory. Due to the ability of proton beams to generate images of strong magnetic fields, the planned application of proton radiography to the Zebra will provide unique data on the evolution of instabilities in z-pinch plasmas and small-diameter liners. A technique used previously to probe magnetic fields in plasmas, Faraday rotation of laser probe beams, has limited application to z-pinch plasmas since it cannot be used in high-density plasma where the largest magnetic fields are expected to exist. We have planned experiments to optimize proton-beam production. To increase scientific productivity, these experiments and others planned to optimize x-rays for radiography will be conducted in a stand-alone laser target chamber that is separate from the Zebra.

Combining the 50 TW/ 20 J laser with the Zebra will also provide unique opportunities for studying the deposition of high-intensity laser light into magnetized and pre-compressed plasma.

III. SYSTEM REQUIREMENTS

The most essential performance requirements of the laser system, as driven by the needs of the planned experiments, are as follows:

- Peak irradiance on target > 10^{19} W/cm^2 to enable generation of energetic proton beams for proton radiography
- Pre-pulse irradiance < 10^{11} W/cm^2 to inhibit formation of plasma at the target prior to short pulse arrival and to enhance proton beam generation
- Pointing accuracy of ± 25 μm to allow laser interaction with an imploded-liner z-pinch target
- Timing jitter relative to the z-pinch < 10 ns to ensure evolution of events driven by the z-pinch can be diagnosed with adequate temporal resolution and repeatability.
- Shot rate > 2 / hr to equal the maximum expected shot rate of the z-pinch (1 / hr) and to allow for at least one laser calibration shot between successive z-pinch shots

IV. LASER DESIGN

Figure 1 shows a schematic diagram of our laser design, which uses a chirped-pulse amplification (CPA) laser architecture. A commercial mode-locked Nd:glass oscillator generates 3-nJ, 200-fs, 8.5-nm pulses at a rate of 100 MHz. A Pockels cell selects single pulses and a Faraday isolator protects the oscillator from back pulses. Pulses are stretched to ~ 1.1-ns duration by an all-reflective grating stretcher. This stretcher design, which is from LULI[1], uses all-reflective Offner-triplet optics and a single gold grating with a groove density of 1740/m. The beam encounters the grating four times, the first time at an angle of incidence of 72.5°.

Two stages of optical parametric chirped-pulse amplification (OPCPA)[2-4] follow the stretcher. The first stage uses critical phase matching in two 10-mm cubic BBO crystals that are oriented in the alternating z-axis configuration, to compensate for walk-off between the pump and signal beams. With a 100-mJ, 5-ns pump pulse at 527 nm, predicted signal-pulse energy from the first-stage OPCPA is 1 mJ. The second OPCPA stage uses a single 10-mm x 10-mm x 15-mm BBO crystal, also set for critical phase matching. With a 500-mJ pump pulse, predicted signal-pulse energy is 60 mJ. The signal-pulse energy required to drive the laser beamline is only 12 mJ. However, energies in the range 20-60 mJ, when delivered at a repetition rate of 5 Hz, facilitate alignment of plasma diagnostics as well as the stretcher and compressor. Gain saturation in the second stage causes the amplified pulse to have flat distributions both temporally and spectrally, with pulse duration and bandwidth of 1.9 ns 16 nm, respectively. Bandwidth is determined by spectral clipping in the stretcher. Both OPCPA stages use a pump-pulse irradiance of about 0.4 GW/cm2, sufficient for efficient amplification but well below damage thresholds for BBO.

Pump pulses for the OPCPA stages are generated with a 1053-nm fiber pulse generator, a Nd:YLF regenerative amplifier with a 4-mm-diameter rod, and a four-pass Nd:YLF amplifier with two 12.7-mm-diameter rods. An electro-optic modulator in the fiber

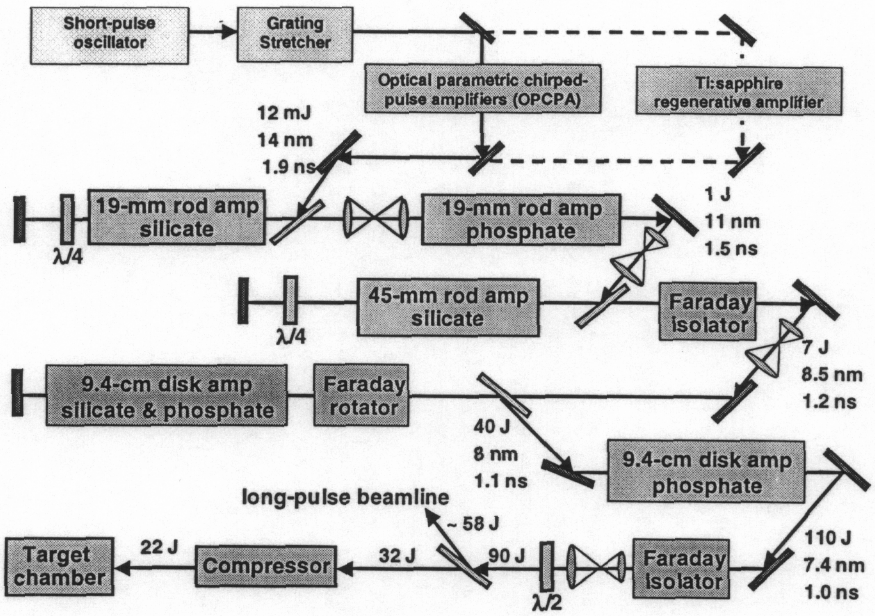

Figure 1. Our chirped-pulse amplification (CPA) laser design uses an optical parametric chirped-pulse amplifier (OPCPA) for pre-amplification and phosphate Nd:glass rod amplifiers for final amplification. A Ti:sapphire regenerative amplifier will be used for initial system activation and to serve as a backup to the OPCPA preamplifier.

pulse generator applies shaping to compensate for gain saturation, so that output pulses from the four-pass amplifier are temporally flat, with durations of 5-ns. The four-pass amplifier uses a phase-conjugate mirror to improve wavefront quality. Predicted output energies for the regenerative amplifier, four-pass amplifier, and subsequent BBO harmonic converter are 2 mJ, 800 mJ, and 640 mJ, respectively. Output from the harmonic converter is split into pulses of 100 mJ and 500 mJ pulses that are delivered to the first and second OPCPA stages, respectively.

A chain of Nd:glass rod and disk amplifiers amplifies the chirped pulse to high energy. To maintain broad bandwidth, both silicate and phosphate glasses are used. The chain comprises a double-pass 19-mm silicate-glass rod amplifier, a single-pass 19-mm phosphate-glass amplifier, and a double-pass 45-mm silicate glass amplifier. A double-pass 9.4-cm disk amplifier, with three silicate-glass disks and three phosphate-glass disks, follows. A single-pass 9.4-cm disk amplifier, with six phosphate-glass disks, provides final amplification. Faraday isolators located after the final rod amplifier and after the final disk amplifier protect laser components from damage due to back-reflected pulses. Image relaying and spatial filtering is used between amplifier stages to maintain good beam quality.

Laser performance was predicted with Quickprop, a 1-D Frantz-Nodvik code that calculates pulse energies at user-specified limits for non-linear phase shift (ΣB) and damage risk (ratio of spatially-averaged fluence to damage-threshold fluence). Output energies given in Figure 1 at various amplifier stages correspond to ΣB of 1.5 radians and to maximum ratio of spatially-averaged fluence to damage fluence of 0.67, which occurs at the last disk of the single-pass 9.4-cm disk amplifier. Disks in the amplifiers were assumed to contain Pt particles, for which damage fluences of ~ 2.5 J/cm^2 have been measured for 1-ns pulses.

Figure 2 shows the predicted output spectrum for the final 9.4-cm disk amplifier, which has a FWHM bandwidth of 7.4 nm. Quickprop calculates spectra using a homogenous-broadening model and infers gain spectra for silicate and phosphate glasses from measured fluorescence spectra. Since gain saturation is small, with square pulse distortion of ~1.7, the effect of the homogeneous-broadening model on the spectrum is also small.

Following the 9.4-cm disk amplifiers, the beam is spatially filtered, transmitted through a Faraday isolator, and split, with some 50 J being delivered to a long pulse beam for making plasma and 32 J being delivered to a roof-mirror compressor. This is the maximum energy that can be delivered while keeping the ratio of spatially-average fluence to damage-threshold fluence less than 0.67 on the final grating. The compressor uses two gold, 21 cm x 42 cm gratings.

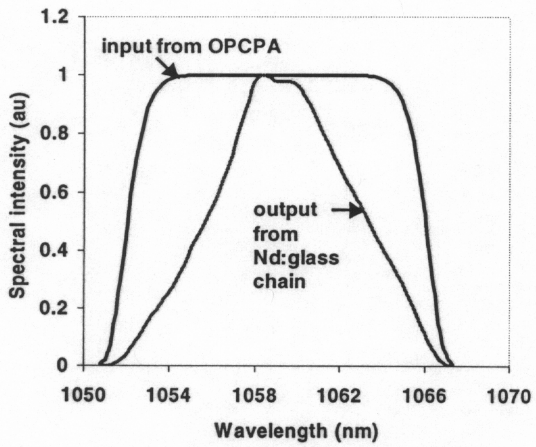

Figure 2. Quickprop predicts the output from the mixed-glass chain to have a somewhat triangular shape, with a FWHM bandwidth of 7.4 nm. The input spectrum was flat over most of its extent, which is characteristic of the output from saturated optical parametric amplifiers.

IV. TARGET AREA DESIGN

Figure 3 shows our conceptual target area design. A 1-m-diameter vacuum target chamber rests atop the Zebra power conditioning system's pulse forming line and encloses a ~ 2 MA z-pinch. The laser beam, which has a diameter of 9 cm, travels from the compressor to the target chamber in an evacuated tube and is focused onto a target by an off-axis parabolic reflector with a 30-cm focal length. Proton beams are generated by focusing the laser beam onto the back surfaces of thin metal foil. X-rays are generated by focusing the laser beam onto the front surfaces of foils made of high-Z materials. Radio-chromic film or plastic track detectors will be used to generate proton radiographs, while x-ray-sensitive film or charged-coupled-device (CCD) cameras will be used to make x-ray radiographs. Alternatively, the beam can be focused directly onto the z-pinch plasma to study laser energy deposition processes.

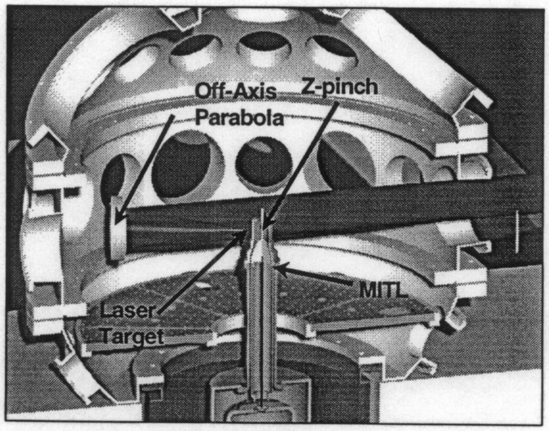

Figure 3. Our design uses a 1-m-diameter vacuum target chamber resting on top of the Zebra power conditioning system.

V. ACKNOWLEDGEMENTS

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